A Brief Historical Analysis of Heat Loss in Aluminium Reduction Cells in China

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Abstract

This paper analyses the variation trends of heat loss in prebaked aluminium reduction cells over the past 25 years, dividing the changes of heat loss into four stages. Statistical analysis and data mining were conducted on the energy balance test results of electrolytic cells in each stage, revealing the corresponding variation characteristics of heat loss. In the first stage (2000–2009), the heat loss of electrolytic cells ranged from 1.9–2.1 V. During the second stage (2010–2014), the heat loss of electrolytic cells decreased to a range of 1.8–1.9 V. The third stage (2015–2021) saw a heat loss of 1.7–1.8 V. In the fourth stage (2022–present), the heat loss dropped to 1.5–1.7 V, demonstrating an overall continuous downward trend. This research provides a reference for future energy-saving and energy balance management strategies in prebaked anode aluminium reduction cells.

Keywords: Aluminium reduction cell, Heat loss, Energy balance.

1. Introduction

In the calculation and analysis of the energy balance for prebaked aluminium reduction cells, the electrolysis temperature is used as the reference temperature. The energy input includes electrical energy input and the energy generated by additional consumption of anode carbon blocks. The electrical energy input refers to the product of the system voltage drop and the current in the electrolysis system, while the additional consumption of anode carbon blocks denotes the energy produced by its oxidation and other reactions beyond the electrolytic reaction. The energy output comprises the energy consumed by the electrolytic reaction of alumina, heat loss from the aluminium reduction cells, energy required for heating the anode, and energy consumed for heating alumina and other raw materials. The energy balance design of electrolytic cells serves as the foundation for cell design, and a well-calibrated energy balance is essential for stable cell operation [1, 3].

In practical electrolysis processes, the energy utilization rate typically remains around 50 %, primarily due to energy dissipation through conduction, radiation, and flue gas emissions, collectively referred to as heat losses in this paper. The magnitude of these losses directly impacts the overall energy consumption of the electrolytic cell. To reduce heat loss, the energy balance design of the electrolytic cell should first optimize the heat dissipation distribution and total heat dissipation to ensure stable operation and energy efficiency and achieve the required heat dissipation during normal operation. Secondly, by measuring the heat dissipation distribution and total heat dissipation of a normally operating electrolytic cell, the rationality of the heat dissipation distribution can be analysed, and optimization measures can be proposed. During the development of prebaked anode aluminium electrolysis process over different periods, the heat dissipation distribution and heat dissipation in the aluminium electrolysis process have evolved with changes in electrolytic cell design concepts.

This paper analyses the trends in heat loss by examining the energy consumption of electrolytic cells over the past 25 years and the energy balance test results of aluminium reduction cells during different stages. The heat loss management technologies applied in aluminium electrolysis across four phases are introduced, providing insights for future energy balance control in aluminium reduction cells and offering new perspectives for further energy conservation and consumption reduction.

2. Trend of Energy Consumption in China's Prebaked Anode Aluminium Reduction Cells

As shown in Figure 1, based on the prebaked anode aluminium electrolysis energy consumption data for China compiled by the International Aluminium Institute (IAI) [4], the trend of energy consumption in China's aluminium electrolysis can be broadly divided into three stages before 2022. The first stage (2000–2009) saw a rapid decline in energy consumption. The second stage (2010–2014) witnessed a steady decrease. The third stage (2015–2021) experienced a continued but slower reduction in energy consumption. Since 2022, under the dual control policies of energy consumption in China and T*he Norm of Energy Consumption per Unit Product of Electrolytic Aluminum and Alumina* (GB 21346-2022), coupled with the sustained rise in remelting aluminium ingot prices, the profitability of aluminium smelters has continued to improve. As a result, the smelters have significantly increased R&D investments. In 2023, China's average comprehensive AC power consumption for aluminium ingots reached 13 324 kWh/t Al, with electrolysis energy consumption continuing to decline rapidly. Therefore, the period from 2022 to the present is classified as the phase 4. The following sections describe the variation characteristics of heat loss in prebaked aluminium reduction cells across these four phases.

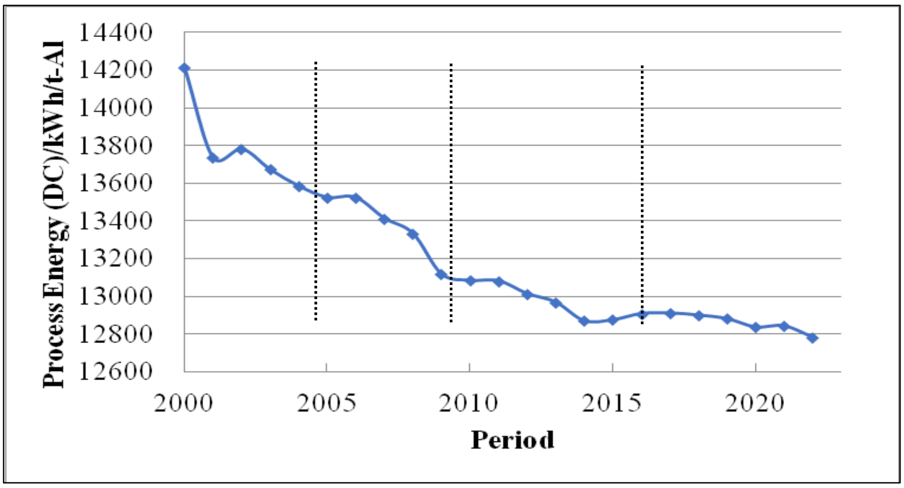

Figure 1. Energy consumption trends in China's aluminium electrolysis industry.

3. Heat Loss Characteristics of Prebaked Anode Aluminium Reduction Cells

In the daily production management of aluminium electrolysis, prebaked aluminium reduction cells are typically divided into zones based on energy balance.

To optimize the energy balance in each zone of the electrolytic cell, energy balance testing and calculations can be conducted to understand the energy distribution characteristics and utilization efficiency in different zones of aluminium reduction cells. This allows for targeted process and production management improvements.

The heat dissipation system of an aluminium reduction cell is generally divided into the anode zone heat dissipation (upper heat dissipation) and the cathode zone heat dissipation (lower heat dissipation) [5]. Corresponding to the energy balance of the cell, the upper heat dissipation includes heat carried away by flue gas as well as heat dissipated through the superstructure, anode rods, cell hoods, and cell ledge plate. The cathode zone heat dissipation comprises side heat dissipation and bottom heat dissipation. The side heat dissipation of the cathode zone includes energy dissipated from the side molten zone, side cathode block zone, side refractory and insulation lining, cathode steel bars, and side cradle frames. The bottom heat dissipation of the cathode zone consists of heat dissipated from the cell bottom and the cradle frame at the bottom of the cell.

The heat loss in the upper section of prebaked anode aluminium reduction cells is related to factors such as the insulation performance of cell cover plates, anode cover material, thermal insulation effectiveness of the cell's large surface, and flue gas flow rate: poor insulation of the cover plates increases heat radiation loss; inadequate thermal insulation of the anode cover material and cell large surface cover material leads to greater direct heat dissipation; and excessive flue gas flow also carries away excessive heat. The heat loss in the lower section, however, is associated with factors such as electrolysis temperature, aluminium and electrolyte levels, ledge thickness, and the refractory and insulation materials of the sidewalls and bottom lining. Maintaining low electrolysis temperature, low aluminium metal level, low electrolyte level, and effective sidewall and bottom insulation can help reduce heat loss in the lower section [6].

4. Heat Loss and Production Technology Status of Prebaked Anode Aluminium Electrolysis in Different Phases

4.1 Phase 1

During the period of 2000–2009, prebaked anode aluminium reduction cells were in their initial development stage, with operational stability being the primary focus. Energy-saving technologies for aluminium electrolysis were limited at the time. With the adoption of anode effect-free low-voltage technology in aluminium electrolysis, the operating voltage of the cell was gradually decreased to around 4.2 V. The heat loss typically ranged 2.0–2.1 V, resulting in a DC power consumption as high as 14 000 kWh/t Al. Table 1 shows the energy efficiency test results of a 280 kA electrolytic cell from a smelter in 2006, with heat loss primarily at 2.0 V. The heat loss in the upper section accounted for 56 % of the total, while that in the lower section constituted approximately 44 %. During this period, energy-saving technologies in the smelters mainly focused on reducing energy consumption through low-voltage techniques that decreased the resistivity of various conductor components. With the widespread adoption of the anode effect-free low-voltage technology in the aluminium industry, the heat loss of electrolytic cells decreased significantly during this phase. The average energy consumption for aluminium electrolysis dropped to 13 118 kWh/t Al in 2009, with cell voltage decreasing to around 4.1 V and heat loss reduced to approximately 1.9 V [7].

Table 1. Energy balance test results of a 280 kA electrolytic cell in a smelter (2006).

	Heat dissipation surface		**Heat dissipation (kW)**	**Heat dissipation (V)**	**%**
Anode zone	Cell hood	Large side cover plate	72.5	0.259	13.1
		Cell ledge cover	8	0.029	1.5
		End face cover plate	5.7	0.02	1
	Subtotal		86.2	0.309	15.5

	Superstructure	Cell top	27.9	0.1	5
		Anode rod	5.2	0.019	0.9
		Flue gas	189.7	0.679	34.2
	Subtotal		222.8	0.797	40.2
	Total		309.1	1.106	55.7
Cathode zone	Side of cathode zone	Melt zone	89.7	0.321	16.2
		Cathode zone	53.2	0.19	9.6
		Refractory and insulation zone	36.4	0.13	6.6
		Cathode steel bar	10	0.036	1.8
		Side cradle frame	17.9	0.064	3.2
	Subtotal		207.2	0.741	37.4
	Bottom of cathode zone	Cell bottom	32.8	0.117	5.9
		Cell bottom cradle frame	5.7	0.02	1
	Subtotal		38.5	0.138	6.9
	Total		245.6	0.879	44.3
Total			554.7	1.985	100

4.2 Phase 2

In 2010–2014, to further reduce the comprehensive energy consumption of aluminium electrolysis, continuous exploration and efforts by industry professionals led to the adoption of technologies such as shaped cathodes and low resistance cathode blocks [8]. The cell voltage gradually decreased from 4.1 V to approximately 3.9 V. The cell heat loss, which was primarily maintained at 1.8–1.9 V, contributed to a DC power consumption of 13 500 kWh/t Al [9, 10]. Over time, the cell heat loss was further reduced to around 1.8 V, showing a significant decline. Table 2 presents the energy balance test results of a 300 kA cell from a smelter in 2011, with a measured heat loss of 1.83 V. The heat loss in the upper section accounted for 55 % of the heat loss, while that in the lower section accounted for 45 %.

Table 2. Energy efficiency test results of a 300 kA electrolytic cell in a smelter in 2011.

Heat dissipation surface			**Heat dissipation (kW)**	**Heat dissipation (V)**	**%**
Anode zone	Cell hood	Large side cover plate	59.4	0.192	10.5
		Cell ledge cover	12	0.039	2.1
		End face cover plate	4.6	0.015	0.8
		Subtotal	76.1	0.246	13.5
	Superstructure	Cell top	29.1	0.094	5.1
		Anode rod	3.8	0.012	0.7
		Flue gas	200.3	0.649	35.4
		Subtotal	233.1	0.755	41.2
	Total		309.2	1.002	54.7
		Melt zone	87.1	0.282	15.4

Cathode zone	Side of cathode zone	Cathode zone	44.8	0.145	7.9
		Refractory and insulation zone	13.9	0.045	2.5
		Cathode steel bar	13.2	0.043	2.3
		Side cradle frame	19.4	0.063	3.4
		Subtotal	178.4	0.578	31.5
	Bottom of cathode zone	Cell bottom	47.5	0.154	8.4
		Cell bottom cradle frame	30.3	0.098	5.4
		Subtotal	77.8	0.252	13.8
	Total		256.2	0.83	45.3
Total			565.4	1.831	100

4.3 Phase 3

From 2015–2021, as China imposed increasingly stringent energy consumption standards and stricter environmental policies on the aluminium electrolysis industry, the industry adopted proactive measures. One of the most significant measures was the continuous development of various energy-saving technologies. Among them, the novel current-stabilizing technology, developed by a smelter, optimizes the synergistic combination of molten aluminium, cathode carbon blocks, steel bars, and assembly to establish a stabilized current flow model. This innovation revolutionized cell design principles by introducing high-conductivity stabilized current steel bars, ultimately forming an energy-efficient aluminium reduction cell system with stabilized current and enhanced thermal insulation. This breakthrough effectively addressed long-standing technical challenges of aluminium reduction cells, such as low current efficiency under reduced voltage and short cell lifespan, achieving substantial energy savings. Additionally, by optimizing the lining design of the cells, the smelter effectively reduced horizontal currents and improved molten aluminium interface stability, maintaining optimal cell performance. This consequently led to a significant reduction in cathode voltage drop [11]. Table 3 shows the energy balance test results of three 300 kA cells from a smelter in 2016. The measured heat losses were all around 1.76 V, with heat loss in the upper section accounting for 56 % and that in the lower section accounting for 44 %. The DC power consumption was 12 900 kWh/t Al. The heat loss was further reduced at this phase, as the optimized bottom insulation layer has decreased the proportion of heat loss contributed by the lower section.

Table 3. Energy efficiency test results of different cell types in a smelter in 2016.

No.		**Cell 1021**		**Cell 2022**		**Cell 3033**	
Cell type		**300 kA**		**400 kA**		**500 kA**	
Zone	**Heat dissipation surface**	**Heat dissipation/V**	**Proportion /%**	**Heat dissipation/V**	**Proportion /%**	**Heat dissipation/V**	**Proportion /%**
Anode zone	Cell hood	0.597	33.6	0.494	27.9	0.603	34.3
	Flue gas	0.302	17.0	0.399	22.6	0.386	22.0
	Total	0.899	50.6	0.893	50.5	0.989	56.3
Cathode zone	Side	0.670	37.7	0.680	38.4	0.622	35.4
	Bottom	0.209	11.8	0.196	11.1	0.146	8.3
	Total	0.879	49.4	0.876	49.5	0.768	43.7
Total		1.778	100.0	1.769	100.0	1.758	100.0

4.4 Phase 4

At the Fifth Plenary Session of the 18th Communist Party of China (CPC) Central Committee, General Secretary Xi Jinping formally introduced the Five Development Concepts: innovation, coordination, green development, openness, and sharing. Among these, green development is a pivotal concept for China's overall progress. The *Norm of Energy Consumption Quota per Unit Product of Electrolytic Aluminium and Alumina* (GB 21346-2022) [12], issued in 2022 and implemented on 1 January, 2024, not only established energy consumption limits for smelters as a national standard but also explicitly defined tiered energy efficiency requirements and expanded the scope of energy consumption statistics for the industry. In 2022, the National Development and Reform Commission (NDRC) issued the *Notice on Improving the Tiered Electricity Pricing Policy for the Electrolytic Aluminium Industry* [13], mandating tiered pricing brackets and prohibiting preferential electricity pricing policy for the industry. Under these national policies, aluminium smelters officially entered the era of dual control over energy consumption. At the time, the industry's average DC power consumption per tonne of molten aluminium often failed to meet the Grade II or even Grade III standards set by the regulations.

To meet the requirements of national strategic planning, aluminium smelters have increased investments in new materials and processes. During this phase, advanced materials and technologies such as heat-reflective thermal insulation coatings for cell hoods [14], novel lining insulation materials [15], graphitic cathodes, and cast-iron casting for cathode assembly have been widely adopted [16]. Further research has been conducted to enhance magnetohydrodynamic (MHD) stability, reduce voltage drop in conductors in various cell components, and refine energy balance design in the cells. Concurrently, improvements in onsite management, optimized thermal insulation, and better alignment of process parameters have collectively contributed to lower energy consumption in the cells [14]. Table 4 presents the energy balance test results of a new 500 kA cell in 2024, comparing to the conventional cell in the same smelter. The measured heat loss was 1.66 V, with heat loss in the upper section accounting for 54 % and that in the lower section accounting for 46 %. The DC power consumption was reduced to 12 300 kWh/t Al. Further reduction in heat loss and DC energy consumption was primarily achieved through technologies such as high-conductivity cathode materials, cast cathode assembly methods, and optimized cell lining design. These improvements significantly decreased heat dissipation, providing robust energy balance support for stable and efficient low-voltage operation of the cells.

Based on the above analysis, over the past 25 years, China's electrolytic aluminium industry has achieved remarkable energy-savings by adopting different technical approaches in different periods to reduce cell heat loss. During phase 1 described in this paper, with the widespread adoption of the anode effect-free low-voltage technology, the cell operating voltage gradually decreased. At this stage, the cell voltage remained relatively high, with substantial electrical energy input, significant heat dissipation pressure, and high flue gas flow rates. The anode zone accounted for approximately 55.7 % of heat dissipation, and the ledge thickness was around 10 cm. This phase primarily focused on reducing cell voltage through anode effect-free low-voltage technology. In phase 2, as aluminium electrolysis researchers shifted their approach, the anode-to-cathode distance (ACD) was reduced to lower voltage drop. The ledge thickness increased to around 13 cm, while heat dissipation in the anode zone decreased to about 54.7 %, with the cathode heat dissipation remaining largely unchanged. During the third and fourth phases, further voltage reduction was achieved by applying aluminium metal flow stabilization technology, graphite-based cathode technology, and cell lining optimization, which reduced voltage drop between anode and cathode as well as voltage drop at the bottom of the cell. The ledge thickness increased to approximately 15 cm and 18 cm, respectively, leading to further reductions in heat loss. In the next five years, with the widespread application of new technologies and materials such as cathode cast-iron casting, copper-embedded collector bars, and novel cast-iron, cell heat loss will be further reduced while achieving additional decreases in cell voltage.

Table 4. Energy efficiency test results of a 500 kA novel graphitized cell in a smelter.

Heat dissipation surface			**Heat dissipation (kW)**	**Heat dissipation (V)**	**%**
Anode zone	Cell hood	Large side cover plate	83.2	0.164	9.9
		Cell ledge cover	48.9	0.097	5.8
		End face cover plate	21.5	0.042	2.6
		Subtotal	153.5	0.304	18.3
	Superstructure	Cell top	69.9	0.138	8.3
		Anode rod	25.1	0.05	3
		Flue gas	205.1	0.406	24.4
		Subtotal	300.1	0.594	35.8
	Total		453.6	0.897	54.1
Cathode zone	Side of cathode zone	Melt zone	151.4	0.299	18
		Cathode zone	76.7	0.152	9.1
		Refractory and insulation zone	20.7	0.041	2.5
		Cathode steel bar	54.5	0.108	6.5
		Side cradle frame	24.8	0.049	3
		Subtotal	328.1	0.649	39.1
	Bottom of cathode zone	Cell bottom	45.1	0.089	5.4
		Cell bottom cradle frame	12.4	0.025	1.5
		Subtotal	57.5	0.114	6.9
	Total		385.6	0.763	45.9
Total			839.2	1.66	100

5. Conclusions

An analysis of energy consumption statistics and energy efficiency test data for prebaked anode aluminium reduction cells back to 2000 reveals the trends in energy consumption and heat loss over the past 25 years. The heat loss characteristics of prebaked anode aluminium reduction cells during this period can be divided into four phases:

1) Phase 1 (2000–2009): The cell heat dissipation was generally 1.9–2.1 V, with DC power consumption as high as 14 000 kWh/t Al.
2) Phase 2 (2010–2014): The cell heat dissipation was generally 1.8–1.9 V, with DC power consumption as high as 13 500 kWh/t Al.
3) Phase 3 (2015–2021): The cell heat dissipation was generally 1.7–1.8 V, with DC power consumption of 12 900 kWh/t Al.
4) Phase 4 (2022-present): The heat dissipation of electrolytic cells is generally 1.5–1.7 V, with DC power consumption of 12 300 kWh/t Al.

The reduction of energy consumption in all stages of aluminium electrolysis, by decreasing heat loss whether in the upper or lower section, relies on the optimization of the overall energy balance technology of the cell.

In the future, on the premise of achieving overall cell energy balance, the continuous application and refinement of new materials and electrolysis processes, along with technologies for recovering wasted energy, high-conductivity busbars and collector bars, and research on reducing interfacial voltage drop in cast-iron, it is expected to further decrease the relative heat loss in the upper and lower sections of the cell. This will ultimately achieve the goal of reducing energy consumption. The study will provide theoretical support and data references for energy-saving improvements in aluminium reduction cells.

6. References

1. Shulan Gao, Weihong Tian, Discussion on the Relationship Between Energy Balance of Aluminium Reduction Cells and Control of Key Technical Parameters, *Light Metals*, September 2013, 42–46.
2. Changlin Li et al., Energy Balance for the aluminium reduction cell Heat Balance[C]//*Light Metals*, Low Voltage, 2021. TMS, 2021: 413–418.
3. Bin Fang et al., Production Management of Aluminium Electrolysis at Super Low Voltage[C]// *Light Metal* 2021, TMS, 2021: 419–422.
4. International Aluminium Institute, Primary aluminium smelting energy intensity [EB/OL], https://international-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/.
5. Junqing Wang, Changlin Li, and Yunfeng Zhou, Study on the Ideal Low Heat Dissipation State of Aluminium Reduction Cells, *Light Metals*, May 2019, 26–29.
6. Chunhuan Li, Alin Cao, Energy Balance Analysis of 400 kA Potline Aluminium Reduction Cells, *Nonferrous Metals (Extractive Metallurgy)*, April 2017, 30–34.
7. Zhengzhou Research Institute of CHALCO, Comprehensive Testing and Energy-Saving Potential Research Report on Aluminium Electrolysis, Zhengzhou: Zhengzhou Research Institute of CHALCO, 2007–2012.
8. Wenjie Yang, Zhirong Shi, and Qingguo Jiao, Current Status and Considerations of Energy-Saving Technologies in Aluminium Electrolysis [J], *Light Metals*, 2012, (5): 26–30.
9. Zhirong Shi, Dengpeng Chai, and Yunfeng Zhou, Development and Application of Energy-Saving Technology for New-Type Stable-Current and Heat-Conserving Aluminium Reduction Cells, *2016 Achievement Appraisal Report by China Nonferrous Metals Industry Association*.
10. Shilin Qiu et al., Development and Application of Energy-Saving Technologies for Aluminium Electrolysis with Lower Energy Consumption [R], *2018 Achievement Appraisal Report by China Nonferrous Metals Industry Association*.
11. Yanfang Wang, Dengpeng Chai, and Shaofeng Cao, Development of a Novel Energy-Saving Technology for Electrolytic Cells with Stable Current and Thermal Balance & Its Application in a 400 kA Electrolysis Series, *Nonferrous Metals (Extractive Metallurgy)*, July 2020, 46–52.
12. GB 21346-2022, Norm of Energy Consumption Per Unit Product of Electrolytic Aluminium and Alumina [S], Beijing: National Technical Committee on Energy Fundamentals and Management, 2022.
13. Notice of the National Development and Reform Commission on Improving the Tiered Electricity Pricing Policy for the Electrolytic Aluminium Industry - Departmental Documents of the State Council_ Government of China (www.gov.cn) [Z/OL], (August 28, 2021), https: //www.gov.cn/zhengce/zhengceku/2021-08/28/content_5633903.htm.

14. Yang Zhang, Yanan Zhang, and Bin Fang, Energy-Saving Potential Analysis and Application Practice in Aluminium Reduction Cells, *Nonferrous Metals (Extractive Metallurgy)*, August 2023, 43–49.
15. Xi Cao, Hongwu Hu, Yafeng Liu, Construction of Green and Low-Carbon Technology System for Aluminium Electrolysis Under Dual-Carbon Background, *Light Metals*, February 2024, 18–23.
16. Wei Chen, Application of Graphitized Cathodes in 400 kA Series Aluminium Reduction Cells, *Nonferrous Metals (Extractive Metallurgy)*, 2024, (06): 53–58.